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1. INTRODUCTION

Write introduction to the topic

2. GEOMETRIC MODEL OF SCHEIMPFLUG IMAGING

A. Geometric Properties of Image for Tilted Lens and Sensor

1. Transfer of chief rays’ direction cosine from entrance to exit pupil

The schematic in Fig. 1 represents a camera in terms of the paraxial pupil planes of a lens along the image plane. The lens is pivoted the point . We have overloaded the notation to also represent the coordinate frame of the camera. The pivot of the lens (equivalently, the optical axis) is the origin of . The centers of paraxial entrance and exit pupils—represented by and —lie along the optical axis at distances and respectively from . The diameters of entrance and exit pupils are represented as and respectively. The image plane is pivoted about at the point in the camera frame . This point, represented by is the origin of the two-dimensional image coordinate frame, also represented by . The figure also depicts two rays from the object space to the image space that are fundamental to geometric optics modeling—the chief ray and the marginal ray.

The chief ray which originates at the object point in the object space with direction cosine passes through the center of the entrance pupil , reemerges from the exit pupil with direction cosine , and intersects the image plane at . Are the input and out direction cosine vectors and equal? In other words, suppose the chief ray in the object and image space makes angles and with the optical axis, then is and have the same absolute value? To answer this question, we consider the marginal rays and the pupils. Suppose, the marginal ray in the object space, which originates from the base (projection) of the object point on the optical axis and travels to the edge of the paraxial entrance pupil at height , makes an angle with the optical axis. In the image space, let us suppose, the marginal ray from the edge of the exit pupil at height to the base of the image point on the optical axis makes an angle with the optical axis. Then, if and (generally the case in macroscopic imaging), then we obtain:

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Note although the image point , by definition, lie on the image plane, its projection on the the optical axis lie on the image plane only in the special case when the optical axis is perpendicular to the image plane.

Now, , the ratio of the paraxial exit pupil height to the entrance pupil height is defined as the *pupil magnification* [ref]. Further, according to the *Lagrange invariant* property [ref] of the two rays (the chief ray and the marginal ray) the transverse magnification () is reciprocal to the angular magnification (). Therefore, Eq. (1) reduces to:

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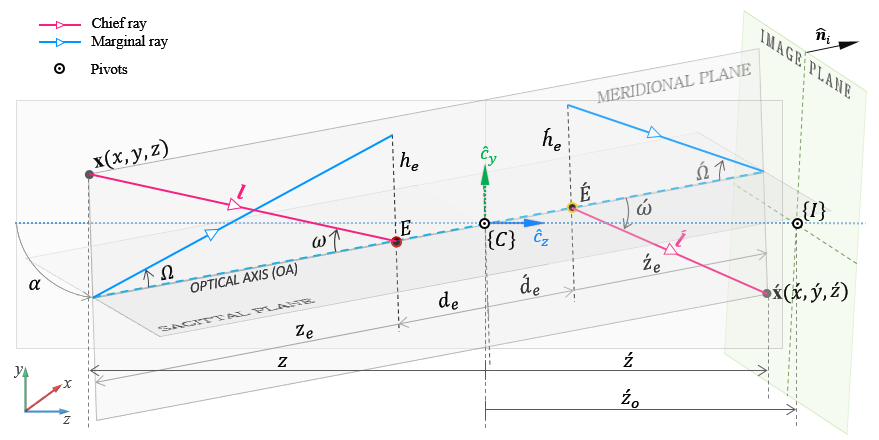
Equation (2), also derived in [ref] using a different approach, implies that the angle of emergence of the pencil of chief rays from the exit pupil towards the image plane depends on the pupil magnification.

To derive the relation between the object and image space direction cosine of the chief ray— and —let us first suppose that the optical axis is coincident with the z-axis of . Consequently, the zenith angle of all chief rays in the object space and all chief rays in the image space are and respectively. For any specific chief ray if the azimuthal angles in the object and image space are and respectively, and if and , then we obtain:

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Following few algebraic steps using Eq. (2), Eq. (3) and the fact that the chief ray in the object and image space is confined to the same meridional plane (i.e., ) [ref], we obtain:

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 Fig. 1. Schematic of the general optical system with the lens pivoted at and the image plane pivoted at .

We can write Eq. (4) compactly as:

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where, . Further, we can safely drop the negative sign in Eq. (5) since the ray emerging from the exit pupil travels in the direction of positive z-axis towards the image plane.

To derive the general expression for the transfer of chief ray’s direction cosine, we first introduce —the rotation matrix applied to the optical axis to rotate the lens about the pivot . We also introduce a new coordinate frame, sharing its origin with , but fixed to the lens such that the z-axis of is coincident with the optical axis. The pupils and the frame rotate along with the optical axis. As before, we represent the input direction cosine of the chief ray in frame as . The vector in frame becomes . As a result,, the z-component of , becomes , where is the third column of . Using Eq. (5) we obtain the output direction cosine of the chief ray in frame as:

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Finally, we obtain the output direction cosine of the chief ray, in the camera frame , that emerges from the exit pupil as :

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where, .

We expect the direction cosine to have unit magnitude. It is indeed straightforward to show the -Norm of is equal to one, and is the normalizing term. Note that if the pupil magnification of the lens is equal to one, then , which implies that the opening angles of the image and object space perspective cones are equal irrespective of the orientation of the optical axis. In terms of geometric optics, also implies that the paraxial entrance and exit pupil planes are coincident with the front and rear principal planes respectively. Such lenses in which are called symmetric lenses.

2. Expression of image point for arbitrary orientation of lens and image planes

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If the entrance and exit pupils are located at distances and from the pivot (origin of ) along the optical axis, then following rotation of the optical axis, the locations of the entrance and exit pupils in the frame is andrespectively. Further, we express the chief ray emerging from the exit pupil as , where the parameter determines the length of the ray. Substituting Eq. (7) for we obtain:

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We would like to determine the expression for for which . Let be the perpendicular distance of the image plane, with surface normal , from the origin of . Then, represents the equation of the image plane in in Hessian normal form. Therefore, when , we obtain:

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Further, if we represent the orientation of the image plane by , then . Also, since the point lies on the image plane, we can write .

Substituting Eq. (9) into Eq. (8) and using we obtain the expression for the image point as:

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Let the location of the entrance pupil in be Then,

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1. T. Ireno and R. Tadaa, "Chemical and mineral compositions of sediments from ODP Site 127-797" (Geological Institute, University of Tokyo, 2009), [**http://dx.doi.org/10.1594/PANGAEA.726855**](http://dx.doi.org/10.1594/PANGAEA.726855).

**Sample code citation**

1. Zima Engineering, ZIMA-CAD-Parts: Application for management of CAD files and projects (version 0.5.0-beta1) [software] (2013), [**http://sourceforge.net/projects/zima-cad-parts/**](http://sourceforge.net/projects/zima-cad-parts/).

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